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ADVANCEMENTS OF PARTICLE FILTERING THEORY AND ITS APPLICATION TO TRACKING

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1 Brief summary of the proposed research

The main goal of this work is the development of a general class of particle filtering methods and apply them to various problems related to target tracking. Theoretically, the project involves the advancement of existing particle filtering schemes and the development of new ones that relax the probabilistic assumptions of the standard methods. The design of the new filters is guided by the objectives of securing (a) excellent performance in target tracking in most demanding situations, (b) robustness, and (c) relatively easy hardware implementation. Practical efforts include applications of the filters to tracking of single targets as well as to much more challenging tasks such as tracking of multiple targets where the number of targets may vary with time. Finally, scenarios that require multisensor tracking and data fusion are also of interest.

2 Accomplished work

- *On the design of generalized particle filters.*

  We investigated the relationship between a special class of generalized particle filters and the standard particle filters. In particular, we examined the conditions for which the generalized particle filters become standard particle filters and when they produce identical results. The analysis provided a better understanding of the new methodology and showed a way to derive new convergent algorithms.

- *Particle generation, cost assignment, and resampling.*

  The generalized particle filters implement the same three steps as the standard particle filters: particle generation, cost (weight) computation of particles, and resampling. The proposal of new particles is typically achieved by one of several methods. Without a good proposal function for particles, the performance of any particle filter is likely to be inaccurate. We have studied two new approaches for generation of new particles. The main focus of these methods was to obtain particles such that the state space was adequately explored and which should lead to more robust performance. The new algorithms were applied to target tracking in a wireless sensor network. As for cost assignment, our efforts were geared towards finding cost functions that had robust features. A related issue, which was also investigated included finding new robust estimators of the

unknown states and static parameters. Finally, we also worked on resampling. Resampling is an indispensable algorithmic component of the particle filters but also a major obstacle for efficient implementation with parallel VLSI hardware devices because it creates full data dependencies among the used processing units. Therefore, we have explored methods for avoiding resampling in the classical sense altogether.

- *Study of various implementations.*

  We investigated different variants of the generalized particle filters by introducing some suitable and natural modifications in order to increase their efficiency and reduce their computational complexity. The advantages of the obtained alternatives were discussed and their validity was demonstrated by application of the algorithms to the problems of target positioning and maneuvering target tracking. We also applied the obtained algorithms and other further simplified schemes to the problem of tracking of multiple targets which move along a two-dimensional space.

- *Convergence.*

  We already have some result on convergence of the generalized particle filters which hold under rather strict assumptions.

- *Fixed parameter estimation.*

  Standard particle filters cannot properly handle dynamic systems with unknown fixed parameters. We extended the methodology to jointly estimate the time-varying state and the static parameters of a dynamic system. In particular, we found three strategies that allowed for assigning costs to the random samples in the state-space independently of the fixed parameters. Asymptotic results that established relationships among the methods were derived, and computer simulation results illustrating their practical implementation in a vehicle navigation problem were obtained.

- *Nonlinear and conditionally linear states*

  In many problems in science and engineering, the used dynamic systems may have some states that are conditionally linear given the nonlinear states of the system. This allows for improved filtering of the unknown states. In the literature on standard particle filtering, methods that exploit the conditional linearity are known as Rao-Blackwellized particle filters. We found how we can exploit this special structure of the dynamic system in the context of generalized particle filters.

- *Applications*

  The generalize particle filtering algorithms were applied to the problem of tracking in different contexts:

  - Maneuvering target tracking
  - Bearings-only tracking
  - Unknown number of targets
  - Wireless binary and tertiary sensor networks

  For all the considered scenarios, we compared the proposed methods with standard particle filtering and other classical methods like the extended Kalman filter.

3 Future work

- *Convergence issues.*

We will try to establish convergence results under milder assumptions that are easier to grasp and that allow for developing a constructive method for proving convergence.

- *High dimensionality of the state space.*

  One critical issue of particle filtering is the dimensionality of the state space. It is well known that as the dimension of the state space increases, the number of necessary particles needed for acceptable performance of the particle filters increases considerably. We will research approaches where the state space is partitioned into smaller state spaces and where for each state space we have an independent particle filter.

- *Extensions to batch type signal processing and optimization.*

  The general class of particle filters can also be applied to problems which are not sequential in nature. The recursions will be now iterations, and the distribution of costs from the last iteration will serve as inputs for producing better discrete measures (with nodes that lower average costs). This does resemble the philosophy of the population Monte Carlo (PMC) method. We will work on the use of the general particle filters for batch signal processing and will compare it with the PMC.

- *Connections to learning theory.*

  Even though in the development of general particle filters we formally do not use the Bayesian paradigm, learning takes place as observations are processed. We will try to establish the learning mechanism of general particle filtering and formally describe and rationalize it. We will study the link between stochastic correlative learning and the theory of general particle filters. We will also examine the possibility of creating a cost-based rule for which the Bayes' rule is a special case.

4 Activities

4.1 Invited talks

1. P. M. Djurić, "Bearings-only tracking based on multiple sensor measurements and generalized particle filtering" accepted in the 2006 Asilomar Conference on Signals, Systems, and Computers, Pacific Grove (California, USA), October 2006.

2. P. M. Djurić, "Tracking in binary and tertiary sensor networks", Workshop on Sensor Networks, Paris (France), September 2006.

3. P. M. Djurić, "Cost-reference particle filtering for dynamic systems with nonlinear and conditionally linear states," Nonlinear Statistical Signal Processing Workshop 2006 (NSSPW 2006), Cambridge (UK), September 2006.

4.2 Presentations at conferences/workshops

1. "Advantages of cost-reference particle filters for multiple target tracking," 14th European Signal Processing Conference (EUSIPCO 2006), Florence (Italy), September 2006.

2. "On the robustness of cost-reference particle filtering," Fourth IEEE Workshop on Sensor Array and Multi-Channel Processing (SAM 2006), Boston (Massachusetts, USA), July 2006.

3. "Fusion of information for sensor self-localization by a Monte Carlo method," 9-th International Conference on Information Fusion, Florence (Italy) July 2006.

4. "Tracking of time-varying number of moving targets in wireless sensor fields by particle filtering," IEEE International Conference on Acoustics, Speech, and Signal Processing, Toulouse (France), May 2006.

5. "Maneuvering target tracking with simplified cost reference particle filters," IEEE 31st International Conference on Acoustics, Speech and Signal Processing (ICASSP'2006), Toulouse (France), May 2006.

6. "Target Tracking in a Two-Tiered Hierarchical Sensor Network," IEEE International Conference on Acoustics, Speech, and Signal Processing, Toulouse (France), May 2006.

7. "Comparison of EKF- and PF-based methods in tracking maneuvering targets," 2006 IEEE Aerospace Conference, Big Sky (Montana, USA), March 2006.

8. "Positioning by cost reference particle filters: study of various implementations," 2005 International Conference on "Computer as a tool" (EUROCON), Belgrade (Serbia and Montenegro), November 2005.

9. "Novel particle filtering algorithms for fixed parameter estimation in dynamic systems," 4th International Symposium on Image and Signal Processing and Analysis (ISPA), Zagreb (Croatia), September 2005.

4.3 Journal papers

1. P. M. Djurić, M. Vemula, M. F. Bugallo, "Binary sensor networks: target tracking by particle filtering," submitted to IEEE Transactions on Signal Processing, August 2006.

2. M. F. Bugallo, S. Xu, P. M. Djurić, "Performance comparison of EKF and particle filtering methods for maneuvering targets," to be published in Digital Signal Processing.

4.4 Conference papers

1. P. M. Djurić and M. F. Bugallo, "Bearings-only tracking based on multiple sensor measurements and generalized particle filtering" accepted in the 2006 Asilomar Conference on Signals, Systems, and Computers, Pacific Grove (California, USA), October 2006.

2. P. M. Djurić and M. F. Bugallo, "Cost-reference particle filtering for dynamic systems with nonlinear and conditionally linear states," accepted in the Nonlinear Statistical Signal Processing Workshop 2006 (NSSPW 2006), Cambridge (UK), September 2006.

3. M. F. Bugallo and P. M. Djurić, "Advantages of cost-reference particle filters for multiple target tracking," Proceedings of the 14th European Signal Processing Conference (EUSIPCO 2006), Florence (Italy), September 2006.

4. M. F. Bugallo, M. Vemula and P. M. Djurić, "On the robustness of cost-reference particle filtering," Proceedings of the Fourth IEEE Workshop on Sensor Array and Multi-Channel Processing (SAM 2006), Boston (Massachusetts, USA), July 2006.

5. M. Vemula, M. F. Bugallo, and P. M. Djurić, "Fusion of information for sensor self-localization by a Monte Carlo method," Proceedings of the 9-th International Conference on Information Fusion, Florence, Italy, 2006.

6. M. F. Bugallo and P. M. Djurić, "Tracking of time-varying number of moving targets in wireless sensor fields by particle filtering," Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing, Toulouse, France, 2006.

7. S. Xu, M. F. Bugallo, and P. M. Djurić, "Maneuvering target tracking with simplified cost reference particle filters," Proceedings of the IEEE 31st International Conference on Acoustics, Speech and Signal Processing (ICASSP'2006), Toulouse (France), May 2006.

8. M. Vemula, M. F. Bugallo, and P. M. Djurić, "Target Tracking in a Two-Tiered Hierarchical Sensor Network," Proceedings of the IEEE 31st International Conference on Acoustics, Speech and Signal Processing (ICASSP'2006), Toulouse (France), May 2006.

9. M. F. Bugallo, S. Xu, P. M. Djurić, "Comparison of EKF- and PF-based methods in tracking maneuvering targets," Proceedings of the 2006 IEEE Aerospace Conference, Big Sky (Montana, USA), March 2006.

10. M. F. Bugallo, J. Mguez, P. M. Djurić, "Positioning by cost reference particle filters: study of various implementations," Proceedings of the 2005 International Conference on "Computer as a tool" (EUROCON), Belgrade (Serbia and Montenegro), November 2005.

11. J. Mguez, M. F. Bugallo, P. M. Djurić, "Novel particle filtering algorithms for fixed parameter estimation in dynamic systems," Proceedings of the 4th International Symposium on Image and Signal Processing and Analysis (ISPA), Zagreb (Croatia), September 2005.

4.5 Accepted papers

1. M. F. Bugallo, T. Lu and P. M. Djurić, "Advantages of Cost-Reference Particle Filters for Multiple Target Tracking," accepted in the 2007 IEEE Aerospace Conference, Big Sky (Montana, USA), March 2007.

4.6 Special sessions related to the work organized at conferences/workshops

1. "Advances in Monte Carlo methods for target tracking," 14th European Signal Processing Conference (EUSIPCO 2006), Florence (Italy), September 2006.

2. "Monte Carlo-based methods for sensor signal processing," IEEE Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP), Puerto Vallarta (Mexico), December 2005.